Spectroscopic observations of convective patterns in the atmospheres of metal-poor stars

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ABSTRACT

Convective line asymmetries in the optical spectrum of two metal-poor stars, Gmb1830 and HD140283, are compared to those observed for solar metallicity stars. The line bisectors of the most metal-poor star, the subgiant HD140283, show a significantly larger velocity span that the expectations for a solar-metallicity star of the same spectral type and luminosity class. The enhanced line asymmetries are interpreted as the signature of the lower metal content, and therefore opacity, in the convective photospheric patterns. These findings point out the importance of the three-dimensional convective velocity fields in the interpretation of the observed line asymmetries in metal-poor stars, and in particular, urge for caution when deriving isotopic ratios from observed line shapes and shifts using one-dimensional model atmospheres.

The mean line bisector of the photospheric atomic lines is compared with those measured for the strong Mg I b_1 and b_2 features. The upper part of the bisectors are similar, and assuming they overlap, the bottom end of the stronger lines, which are formed higher in the atmosphere, goes much further to the red. This is in agreement with the expected decreasing of the convective blue-shifts in upper atmospheric layers, and compatible with the high velocity redshifts observed in the chromosphere, transition region, and corona of late-type stars.

Subject headings: line: profiles – radiative transfer – Sun: photosphere – stars: atmospheres – stars: late-type

1. Introduction

The solar granulation pattern observed by direct imaging in the optical continuum is the result of the convective motions in the solar envelope. The velocity fields and spatial patterns present in the solar photosphere leave a signature on spectra, even when they lack spatial resolution. Line asymmetries reveal similar shapes for most lines (Dravins, Lindegren & Norlund 1981), while line shifts become gradually bluer when the line formation occurs deeper in the photosphere (Allende Prieto & García López 1998a, hereafter APGL). These features cannot be realistically explained by any other known mechanism such as isotopic shifts, hyperfine structure, pressure shifts, or line blends.

Similar effects are expected to be present in other stars. Over the last two decades, David Gray and collaborators (see, e.g., Gray 1982, Gray & Toner 1986, Toner & Gray 1988, Gray & Nagel 1989, Gray et al. 1992) and Dainis Dravins (see, e.g., Dravins 1982, 1987a, 1987b) have extended the measurement of line asymmetries to many other stars, confirming the expectations: the shapes of the line bisectors of late-type stars with convective envelopes are similar to the solar case. Surprisingly, opposite curvature are found in the bisectors of hotter stars, which are not expected to develop convective envelopes. The difficulties in obtaining highly accurate radial velocity measurements and the need to separate the radial velocity, the gravitational shift, and convective shifts has precluded the use of absolute line shifts as a tool to probe convection on late-type stars. The use of differential line shifts has already been attempted by Nadeau & Maillard (1988) for M giants.

Gray (1982) and Gray & Toner (1986) identified a sequence in the line asymmetries for late-type dwarfs, giants, and supergiants. Using no information about the line shifts, they averaged line bisectors for lines of different depths at the line center, showing that this method is very useful as a first order approach to understanding the changes of the granular patterns with atmospheric parameters.

In the last two decades, large advance has been made in the modeling of convection in stellar atmospheres. Three-dimensional hydrodynamical numerical simulations of the stellar atmospheres are able now to reproduce the observed line asymmetries, opening up the possibility of understanding convective velocity fields in the photospheres of stars others than the Sun (see, e.g., Nordlund & Dravins 1990). Although empirical models of granulation can be constructed and may be very useful to disentangle the interplay between velocity fields and granulation contrast, full hydrodynamical modeling is the most powerful tool for understanding the physical mechanism behind the observed convective patterns.

Of particular significance is the proper understanding of convection and the effects of convective inhomogeneities in metal-poor stars on the main sequence or close to it (subdwarfs, subgiants). Abundance analyses of such stars are fundamental in the study of primordial nucleosynthesis as well as the early evolution of the Galaxy. In these stars, the convection zones and the resulting inhomogeneities reach visible photospheric layers, mainly due to the high transparency of the gas because of the low electron pressure and the lack of metal absorption in the ultraviolet. The latter circumstance also leads to a hot non-local radiation field in the near ultraviolet which may induce severe departures from local thermodynamic equilibrium (LTE). It is thus very important to explore the effects of convection and departures from LTE in stars of this type.

Detailed comprehension of surface convection in metal-poor stars is of high importance for fine analysis of spectral line shapes, such as the retrieval of isotopic ratios of lithium (Smith, Lambert & Nissen 1998), boron (Rebull et al. 1998), or barium (Magain & Zhao 1993), which have to rely on one-dimensional models that may introduce an important uncertainty.

We have acquired spectra of adequate quality of two metal-poor stars, to address these fundamental questions of whether, or not, the three-dimensional inhomogeneities and the convective velocity motions in the photospheres of metal-poor stars lead to severe errors in the results obtained from the use of one-dimensional model atmospheres in the spectroscopic analysis of of metal-poor stars. In this paper, we select clean profiles, measure, and average line bisectors of different lines in order to compare convection in the photospheres of solar composition and metal-poor stars. After giving the details of the observing and reduction procedure in §2, we shall discuss the solar case and carefully check the quality of the spectroscopic observations in §3. The analysis of line asymmetries in the photospheres of the metal-poor compared to the solar composition stars is the subject of §4, and §5.

2. Observations

We have selected two well-known field stars belonging to the population II: the moderate metallicity dwarf Gmb1830 (HD103095, HR4550; [Fe/H] ~ -1.3; G8 V) and the more metal-poor subgiant HD140283 ([Fe/H] ~ -2.7; G0 IV). The Sun and the solar-like metallicity star θ UMa (HD82328, HR3775; F6 IV) were included in the program to be used as references.

Observations were carried out during three campaigns from 1995 to 1997 using the *2dcoudé* echelle spectrograph (Tull et al. 1995) coupled to the Harlan J. Smith 2.7m Telescope at McDonald Observatory (Mt. Locke, Texas). The cross-disperser and the availability of a 2048x2048 pixels CCD detector made it possible to gather up to 300 Å in a single exposure, in a series of non-overlapping segments. The set-up provided resolving powers ($\lambda/\Delta\lambda$) in the range 170,000-220,000. As many 1/2 hour exposures were acquired as were needed to reach a final signal to noise ratio (SNR) of $\sim$ 300–600. Table 1 describes the three observational campaigns devoted to the program.

A very careful data reduction was applied using the IRAF[2] software package, and con-

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[2]IRAF is distributed by the National Optical Astronomy Observatories, which are oper-

sisted in: overscan (bias) and scattered light substraction, flatfielding, extraction of one-dimensional spectra, wavelength calibration, and continuum normalization. Wavelength calibration was performed for each individual image on the basis of ~ 300 Th-Ar lines spread over the detector. The possibility of acquiring daylight spectra with the same spectrograph allows us to perform a few interesting tests. Comparison of the wavelengths of 60 lines in a single daylight spectrum (SNR $\sim$ 400-600, depending on the spectral order) with the highly accurate wavelengths measured in the solar flux spectrum by Allende Prieto & García López (1998b) showed that the rms differences were at the level of 58 m s^{-1} ($\sim \frac{1}{11}$ pixel).

Before coadding the individual one-dimensional spectra, they were first cross-correlated to correct for the change in Doppler shifts and instrumental displacements, such as those produced by the variation of weight as the CCD's liquid nitrogen dewar empties. Fig. 1 shows the measured shifts between different spectra of HD140283, relative to the first of them, on the night of May 20 1995. The observed shifts (joined by the solid line) do not correspond to those expected from the difference of velocities in the line of sight between the Earth and the Sun, indicated by circles in Fig. 1. Our procedure introduced an uncertainty in the wavelength scale, whose magnitude depends on the SNR, the presence of telluric lines, and the time separation among the individual spectra. When the standard deviation of the velocity shifts from the cross-correlation of the different available orders was below ~ 150 m s^{-1}, the frames were co-added to increase the SNR. This strategy ensures that the errors introduced in the line shifts when co-adding the spectra are of the order of $\frac{150}{\sqrt{N}}$ m s^{-1} or less, where N, the number of useful orders, is in the range 8–17. In this way no significant extra asymmetry is artificially produced.

Fig. 2 demonstrates how well the shifts are determined for the individual spectra of

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HD140283 taken on May 20 1995. The left panel shows the Fe I line at 5393 Å in the different spectra, after correcting the shifts displayed in Fig. 1, while the right panel shows the resulting pattern, ten times magnified, after subtracting the mean spectrum. It is apparent in this figure that no significant residuals remain.

A final test to check that our procedure leads to consistent results is to compare the bisectors measured in the individual exposures with the averaged bisector, and with the bisector measured in the averaged spectrum. This is shown in Fig. 3, for the series in Fig. 1. The average bisector (thick solid line) is in agreement with the bisector of the average line profile (dashed line). The bisectors were averaged using normalized weights $\propto \frac{1}{\sigma^2}$, which corresponds to the weighting performed when co-adding the spectra. While the direct average of the bisectors relative to the line center avoids the shifting of the spectra to the same zero, it requires the location of the centers of the line profiles in the noisy individual exposures, increasing the errors in the final bisector. Alternatively, the final bisector can be measured directly on the averaged spectrum, computed after shifting safely the individual spectra to a common zero through simultaneous cross-correlation of all the spectral orders recorded in a given image. The latter procedure has been adopted in this work.

3. The Sun: accuracy of the measurements

The highest quality high resolution stellar spectra currently available are those of the Sun. The study of line asymmetries and shifts in the optical solar spectrum has been the subject of much work since the early studies of St. John (1928) and Burns and collaborators at Allegheny Observatory (Burns 1929, Burns & Kiess 1929, Burns & Megger 1929). There are recent measurements in the center of the solar disk, at different positions across it, in total flux, and with high spatial and time resolution (see, e.g., Pierce & Breckenridge 1973, Dravins, Lindegren & Norlund 1981, Livingston 1982, Balthasar 1984, Brandt & Solanki

1990, Stathopoulou & Alissandrakis 1993, APGL), but a comprehensive study and classification of the line asymmetries in the flux spectrum of the Sun is still missing. Such a study providing an average solar bisector could serve as a template for comparison with other stars.

Making use of the solar flux spectrum in the atlas of Kurucz et al. (1984), we have measured the line asymmetries of 39 Fe I clean lines selected by Meylan et al. (1993) from the fit of Voigt profiles in the same atlas. The line asymmetries were quantified by means of the bisectors at a given set of flux levels from the continuum. Irregular parts in the line profiles were removed and excluded from the average. All the lines were averaged together, to produce a mean flux bisector, as commonly done with stellar bisectors (Fig. 4; solid line with error bars indicating the mean error). A new average bisector (Fig. 4; solid line with shadow area indicating the mean error) was constructed taking into account the line shifts for Fe I lines measured by APGL from the same atlas, to place the individual bisectors on an absolute scale. In Fig. 4, the *absolute* mean flux bisector has been shifted from its true (bluer) position to overlap with the mean flux bisector computed without taking into account the blue-shifts of the individual lines. The differences between the profiles with and without correction for the velocity shifts are comparable to the precision with which bisectors are measured, but more remarkable, the velocity difference or span between the bluest and the reddest part of the mean bisectors does not change.

As listed in Table 1, we have acquired day-light spectra in different spectral ranges. Figure 5 compares the bisector measured in these spectra (curve with error bars) to that measured in the solar FTS atlas of Kurucz et al. (1984) from three Fe I lines ($\lambda\lambda$ 5217, 5296, and 5933 Å). The agreement is very good, indicating, as expected, that the errors in our measurements are below ~ 60 m s^{-1}. This comparison warranties the adequateness of the procedure employed to remove the scattered light, as this problem is much more important for the day-light spectra than for the stellar spectra. The average of 14 lines in the McDonald day-light spectrum provides a *solar flux mean bisector* quite similar to that previously calculated from the FTS atlas (see below). Here and hereafter, error bars for the bisectors of individual lines are computed following the considerations in Gray (1983).

The convective line asymmetries depend on the velocity fields, the granulation contrast, and the area occupied by the rising granules and the falling intergranular lanes in the line formation layers. As a result of this, convective line asymmetries have been observed to vary with the line depth, the atomic parameters (chemical species, excitation potential, transition probability, etc.), i. e., all those parameters defining the height of the line formation region in the atmosphere. Some spectral lines can be affected by other sources of asymmetry, such as isotopic shifts or hyperfine structure splitting. These are difficult to estimate as accurate laboratory data are missing (see, e.g. Kurucz 1993). Lacking laboratory studies and accurate calculations on collisional broadening, we can not definitely exclude that some lines could be affected by pressure shifts, inducing line asymmetries (Allende Prieto, García López & Trujillo Bueno 1997). These facts make the use of average stellar bisectors questionable. Ideally, detailed modeling of the convective line asymmetries should be carried out by comparison of predicted and observed profiles of individual lines. However, there is a common behavior of the line asymmetries for most of the lines in the solar and stellar spectra and, at least for the solar case, the velocity span of the mean bisector does not change much between taking into account or not the absolute position of the individual lines. Furthermore, there is a remarkably smooth variation of the average stellar bisectors with spectral type and luminosity class (Gray 1982, Gray & Toner 1986). This justifies the use of mean bisectors as a first approach to the classification of the line asymmetries across the HR diagram.

4. Metal-poor stars. Photospheric line asymmetries.

For the most metal-poor star in the sample (HD140283) the task of selecting lines free of blends and anomalous shapes is straightforward, because the lack of metals greatly reduces the overlapping of different lines. For the less metal-poor stars, blending becomes more common, and the selection more difficult. The calculation of an initial average and its standard deviation was made and then a new average, excluding the points deviating significantly from the first average, was calculated. Finally, it was verified that a more critical selection, keeping only the bisectors which exhibited the dominant shape, in all cases, provided almost identical results.

4.1. The dwarf Gmb1830

We have identified a total of 25 clean lines in the spectral range available for Gmb1830 (G8V). Their wavelength, suggested identification, equivalent width, and excitation potential are listed in Table 2. We proceeded as described in the preceding section for the Fe I lines in the solar atlas, and obtained the mean flux bisector for Gmb1830 and the sky-light spectra acquired at McDonald. They are listed in Table 3. Figure 6a shows all the bisectors measured in Gmb1830, and the mean flux bisector for this star, surrounded by error bars, describing the mean error. Figs. 6b is similar to 6a, but for the Sun (from 14 clean lines observed at McDonald). The line bisector shapes are not highly homogeneous but the typical C shape, which can be attributed to the effects of convection, is apparent for most of the lines.

Line bisectors for F-K dwarfs behave in such a way that, although the solar-like C-shape is common for all, the velocity span shows the smallest values around the spectral class G8 (Gray 1982). Direct comparison of the mean bisectors in Figure 7 shows that the mean bisector of Gmb1830 (mean errors represented with error bars) shows a smaller velocity span than that of a *solar metallicity* G2 (the Sun; mean errors in gray). This implies that, for this moderately metal-poor dwarf, we do not detect any significant signature of the lower metallicity in its mean flux bisector.

Rotation strongly affects the shape of the integrated-light line asymmetries (see Gray 1986; Smith, Livingston & Huang 1987; Dravins & Nordlund 1990). However, the rotational velocities of the Sun (1.9 km s^{-1}; Gray 1992) and Gmb1830 (2.2 km s^{-1}; Fekel 1997) are quite close, and then, their asymmetries can be directly compared. Several other factors may be playing a significant role in this comparison. The presence of one or more unresolved companions could well induce systematic line asymmetries in the spectral lines that might be wrongly interpreted as convective patterns. Beardsley, Gatewood, & Kamper (1974) claimed a detection of radial velocity variations in the spectra of Gmb1830, but this claim was not confirmed (Griffin 1984; Heintz 1984). The *Hipparcos* catalogue (ESA 1997) has found the star to show photometric variations spanning 0.14 mag., and although the same catalogue does not register a visual companion for Gmb1830 within 10 arcseconds, it has been claimed in the past (see Beardsley et al. 1974) that the star has a fainter (5-5.5 mag.) companion.

Cyclical activity and magnetic variations are known to be linked to changes in oscillations, and granulation properties (Gray & Baliunas 1995; Jiménez-Reyes et al. 1998). Radick et al. (1998) have detected solar-like periodic variability in the Ca II H and K emission of Gmb1830 with a period close to seven years. The possible differences between the mean bisector of Gmb1830 and the Sun associated with their different metallicities, may indeed have been diluted under some of these effects.

4.2. The subgiant HD140283

As a result of the very low metal content of the star, the high resolution spectrum of HD140283 shows only a few lines. The practical advantage is that the lines present are quite clean. A total of 24 lines were selected in the three spectral ranges available for HD104283 (G0 IV), while only 16 were considered clean in the case of θ UMa (F6 IV), a comparison *solar metallicity* star. The data on the lines selected is also included in Table 2. All the measured bisectors in these stars are plotted in Figure 8, the mean flux bisector is overplotted with the mean error marked by the error bars. Table 4 lists the flux mean bisectors. Almost every line detected in the spectrum of HD140283 was considered clean. The homogeneity of the bisector shape is higher than for the cooler dwarfs studied in the preceding sub-section.

Fig. 9 directly compares the flux mean bisectors for the two stars and the Sun (solid line with the mean error marked in grey). The expectation based on the smooth trends with the spectral class found by Gray (1982) is that the hotter star (θ UMa; F6 IV; dashed line with error bars) should have photospheric bisectors with the larger velocity span. That is in clear contradiction with Fig. 9, where the bisector corresponding to HD140283 (solid line with error bars) shows a red asymmetry as high as ~ 300 m s^{-1}. The obvious suggestion is that the abnormal behavior of the line bisectors measured in the spectrum of HD140283 is the result of its very low metallicity (a factor ~ 500 less than the Sun or θ UMa).

In this case there is a significant difference in the rotational velocities between HD140283 (≤ 3.5 km s^{-1}; Magain & Zhao 1993) and θ UMa (6.4 km s^{-1}; Fekel 1987). This difference is large enough to produce a respectable effect. However, the comparison with the slower Sun (G2 V[3]) is not affected by this parameter, and leads to the same result.

The time span of our observations (three years) suggests that the line asymmetries

[3]Differences between luminosity class V and IV are likely to be negligible (see Gray 1982).

observed in HD140283 are stable. The star has been monitored for radial velocity variations with a negative result (Carney & Latham 1987, Mazeh et al. 1996). θ UMa has been claimed to show periodic radial velocity variations by Abt & Levy (1976), but this has been placed into question by the analysis of Morbey & Griffin (1987).

5. Mg I b_1 and b_2 lines in the spectrum of HD140283

Mean flux bisectors studied in §4 correspond to photospheric lines, and characterize the velocity fields only in this region of the atmosphere. However, velocity fields in upper layers, such as the chromosphere (Samain 1991, García López et al. 1992), the transition region, or the corona (Brekke et al. 1998) of late-type stars have been shown to be much stronger. While the photospheric observed line shifts are directed bluewards and amount a few hundreds meters per second, transition region and coronal lines are shifted to the red by kilometers per second (Wood et al. 1996, Wood, Lynsky & Ayres 1997).

We have measured the asymmetries of the strong MgI b_1 and b_2 lines at 5183 and 5172 Å, respectively, whose cores are known to form higher up than the photospheric layers in the solar atmosphere, in the spectrum of HD140283. The line bisectors are displayed in Fig.10, and compared with the mean flux bisector. In this Figure, the zero velocity is again arbitrarily set to the bottom of the lines. They exhibit a C-shape, although are quite different to the bisectors of the photospheric lines. This could indicate a larger dissimilitude, compared with the photospheric lines, between the velocity fields and the inhomogeneities in the layers where the core and the wings are formed. Assuming the upper part of the photospheric and the strong-line bisectors overlap (as suggested by the shape and the velocity span), the excursion of the line bottom to the red would be tracing the disappearance of the photospheric correlation between temperature and velocity, and therefore the convective blueshift, towards higher atmospheric layers.

Alternatively, the peculiar shape of these bisectors might be the result of the presence of significant contributions of different isotopes of magnesium. There are three magnesium isotopes in the solar-system mixture, ^{24}Mg, ^{25}Mg, and ^{26}Mg, whose abundance fractions are 0.7899, 0.1000, and 0.1101 (Anders & Grevesse 1989), but it is established that the fractions of ^{25}Mg and ^{26}Mg, relative to ^{24}Mg decline with metallicity (Barbuy, Spite & Spite 1987, McWilliam & Lambert 1988), and the resulting asymmetry is expected to be very small for a star like HD140283.

Unlike the solar metallicity stars, the lack of line crowding makes it possible to measure the asymmetries of lines which form between photospheric and chromospheric layers in the extreme metal-poor stars. This could be an important tool to understand how the dynamics of the atmosphere changes from producing blueshifts in the photosphere to redshifts in higher layers. The observations obviously must constrain future three-dimensional simulations of photospheric dynamics further out from the center of the star.

6. Summary and conclusions

We have searched for differences between the convective velocity fields and granular motions of metal-poor stars and solar metallicity stars by observing line asymmetries in the optical spectra at very high resolution.

Clear differences have been found for the most metal-poor star in our sample, probably reflecting the low opacity of the metal deficient atmospheres and the changes in visible convective flow patterns due to this. The line asymmetries found in this case show a significantly different shape as compared with its solar-metallicity counterpart, perfectly distinguishable from the observed line-to-line differences.

The lack of metal line blends and the relatively narrow line wings in metal-poor stars makes it possible to measure the line asymmetries in strong lines such as the Mg I b_1 and b_2, whose cores are formed higher in the atmosphere, possibly revealing a convective pattern rapidly changing with depth which shows up as a markedly redder asymmetry in the line core, as compared with photospheric lines.

Detailed comparison between observed line profiles and three-dimensional numerical simulations of the photospheres of late-type stars, as affected by the underlying convective dynamics, should be a powerful tool to improve the understanding of the atmospheric structure and dynamics of these objects (Allende Prieto et al. 1999, Asplund et al. 1999). Such comparisons should give place to more reliable abundance analyses for these stars.

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FIGURE CAPTIONS

Fig. 1.— Relative displacements in the spectral direction between different exposures of HD140283 on May 20, 1995 (crosses joined by the solid line), and expected shifts due to the Earth-Sun motion (circles).

Fig. 2.— Left panel: individual spectra of the Fe I λ5393 Å line in the spectrum of the star HD140283 on May 20 1995, after removing the relative shifts. The radial velocity has not been corrected. Right panel: remaining residuals after subtracting the mean profile to the individual spectra in the left panel (the vertical scale has been magnified by a factor of ten).

Fig. 3.— The average of the bisectors measured in the individual spectra of HD140283 shown in Fig. 2 (thick solid line), whose shifts are tracked in Fig. 1, is in perfect agreement with the bisector measured in the average profile, constructed after correcting the relative shifts (dashed curve). The thin solid lines show the individual bisectors.

Fig. 4.— The average solar line bisector, constructed from 39 *clean* Fe I lines, with the individual line shifts taken into account (mean errors in grey) and with line shifts not considered (line with error bars).

Fig. 5.— Comparison between the solar bisectors (Fe I, $\lambda\lambda$ 5217, 5296, and 5933 Å), as measured in the FTS atlas of Kurucz et al. (1984; σ represented by the shadow), with those from the day-light spectra acquired at McDonald Observatory (σ represented by error bars).

Fig. 6.— All the measured bisectors for individual atomic lines in the spectra of the Gmb1830 (a), and the Sun (b) are plotted (thin lines). The thick lines represent the *mean flux bisectors*, and the error bars indicate the mean error at a given normalized flux.

Fig. 7.— The mean flux bisector of the metal-poor dwarf Gmb1830 (G8; solid line with error bars) as compared with the hotter Sun (G2; solid line with the mean errors in gray).

Fig. 8.— All the measured bisectors in the spectra of HD140283 (a), and θ UMa (b) (thin lines). The thick lines represent the *mean flux bisectors*, and the error bars indicate the mean error at a given normalized flux.

Fig. 9.— The line bisectors' shape in the spectrum of HD140283 (G0; solid line with error bars). The *mean flux bisector* for the *solar-metallicity* comparison star θ UMa (F6; dashed line) and the Sun (solid line with mean errors in grey) are also shown. The bisector of HD140283 shows a larger velocity amplitude than the metal-rich stars do.

Fig. 10.— The bisectors of the strong Mg I b_1 (deep bisector with error bars) and b_2 (deep bisector with σ in shadow) lines (solid lines), are compared with the flux mean bisector of HD140283. The core of the Mg b lines are formed higher in the atmosphere than the photospheric lines employed for constructing the flux mean bisector as suggested by the remarkable asymmetry to the red, which reveals a change in the velocity-temperature pattern, such as that observed in the solar chromosphere. The absolute position of the bisectors is arbitrary, as the line bottom is assumed to be at zero velocity.

Table 1. Observations: Dates, Spectral Ranges and Signal-to-noise Ratios.

Star	Spectral range (Å)[a]	Date	SNR
Sun	4853-6404	20-May-95	> 500
”	4853-6288	21-May-95	”
”	5204-7037	27-Feb-96	”
”	5549-7875	23-May-97	”
”	4372-5434	24-May-97	”
”	5687-8156	24-May-97	”
”	5687-8156	25-May-97	”
Gmb1830	4853-6404	26-Feb-96	250-350
”	5204-7183	27/29-Feb-96	300-400
HD140283	4850-6400	19-May-95	150-250
”	4850-6400	20-May-95	300-500
”	4850-6400	21-May-95	200-300
”	4424-5497	26-Feb-96	70-100
”	4372-5434	23/24/25-May-97	500-650
θ UMa	5690-8360	26-Feb-96	600

[a]The specified spectral range is not continuous, as the different spectral orders do not overlap.

Table 2. Atomic Spectral Lines Measured

Wavelength (Å)	Species	W_λ (mÅ)	E.P. (eV)
Sun (skylight)			
4950.11	Fe I	96	3.42
5001.87	Fe I	343	3.88
5217.40	Fe I	120	3.21
5296.70	Cr I	98	0.98
5415.21	Fe I	191	4.39
5576.10	Fe I	153	3.43
5701.56	Fe I	84	2.56
5852.23	Fe I	43	4.55
5933.80	Fe I	105	4.64
6151.62	Fe I	50	2.18
6166.44	Ca I	77	2.52
6335.34	Fe I	100	2.20
6336.83	Fe I	126	3.69
6498.95	Fe I	138	0.96
Gmb1830			
4999.51	Ti I	162	0.83
5001.87	Fe I	219	3.88
5083.34	Fe I	130	0.96

Table 2—Continued

Wavelength (Å)	Species	W_λ (mÅ)	E.P. (eV)
5215.19	Fe I	98	3.26
5217.40	Fe I	97	3.21
5225.53	Fe I	59	0.11
5229.86	Fe I	104	3.28
5232.95	Fe I	347	2.94
5302.31	Fe I	125	3.28
5307.37	Fe I	65	1.61
5379.58	Fe I	22	3.69
5381.03	Ti II	26	1.57
5389.49	Fe I	52	4.41
5569.63	Fe I	142	3.42
5662.52	Fe I	77	4.18
5857.45	Ca I	136	2.93
5862.36	Fe I	38	4.55
6162.18	Ca I	440	1.90
6166.44	Ca I	45	2.52
6169.04	Ca I	78	2.52
6169.56	Ca I	212	2.52
6173.34	Fe I	40	2.22
6261.11	Ti I	38	1.43
6270.23	Fe I	18	2.86
6393.61	Fe I	123	2.43

Table 2—Continued

Wavelength (Å)	Species	W_λ (mÅ)	E.P. (eV)
		HD140283	
4434.96	Ca I	45	1.89
4461.66	Fe I	43	0.09
4466.56	Fe I	30	2.83
4468.50	Ti II	77	1.13
4494.57	Fe I	30	2.20
4555.89	Fe II	23	2.83
4563.77	Ti II	50	1.22
4871.33	Fe I	36	2.86
4957.31	Fe I	37	2.85
4957.61	Fe I	110	2.81
5006.12	Fe I	52	2.83
5012.08	Fe I	31	0.86
5171.61	Fe I	40	1.48
5226.87	Fe I	41	3.04
5227.19	Fe I	104	1.56
5232.95	Fe I	46	2.94
5328.05	Fe I	124	0.91
5397.14	Ti I	62	1.88
5405.76	Fe I	69	0.99
5424.08	Fe I	26	4.32
5429.71	Fe I	72	0.96

Table 2—Continued

Wavelength (Å)	Species	W_λ (mÅ)	E.P. (eV)
5434.53	Fe I	54	1.01
5473.92	Ni I	33	1.83
6162.18	Ca I	36	1.90
	θ UMa		
6213.44	Fe I	62	2.22
6219.29	Fe I	74	2.20
6230.74	Fe I	123	2.56
6335.34	Fe I	76	2.20
6336.83	Fe I	80	3.69
6449.82	Ca I	117	2.52
6569.22	Fe I	47	4.73
6707.98	Li I	120	0.00
6717.69	Ca I	94	2.71
6843.66	Fe I	35	4.55
7122.21	Ni I	83	3.54
7286.52	Ni I	145	3.77
7771.96	O I	133	5.37
7774.18	O I	122	4.47
7775.40	O I	97	4.47
7780.56	Fe I	84	4.47

Table 3. Flux Mean Bisectors: Gmb1830 and the Sun (skylight)

	Gmb1830			Sun		
Normalized Flux	Mean Velocity ($m\ s^{-1}$)	Std. Dev. ($m\ s^{-1}$)	Number of lines	Mean Velocity ($m\ s^{-1}$)	Std. Dev. ($m\ s^{-1}$)	Number of lines
0.20	-1.64	16.72	2	...	...	...
0.25	-1.57	1.08	3	...	...	...
0.30	21.76	15.98	3	23.19	2.85	2
0.35	-1.01	8.55	9	2.74	4.94	4
0.40	-2.64	6.22	14	-2.37	3.54	3
0.45	-2.56	7.79	10	-2.69	12.74	8
0.50	-5.67	7.62	10	-7.68	19.16	9
0.55	-9.40	10.72	11	-15.60	24.41	11
0.60	-10.29	10.65	14	-25.85	11.77	10
0.65	-13.26	17.07	18	-32.43	19.05	12
0.70	-17.02	17.77	18	-28.70	22.47	13
0.75	-13.55	28.02	17	-27.80	27.00	13
0.80	-15.08	20.10	17	-20.75	34.82	13
0.85	-7.24	27.15	16	-5.80	48.70	13
0.90	-6.95	25.15	13	14.43	52.70	12
0.92	1.13	13.01	8	37.08	55.73	12
0.95	12.31	18.14	6	73.80	74.58	3

Table 4. Flux Mean Bisectors: HD140283 and θ UMa

	HD140283			θ UMa		
Normalized Flux	Mean Velocity (m s^{-1})	Std. Dev. (m s^{-1})	Number of lines	Mean Velocity (m s^{-1})	Std. Dev. (m s^{-1})	Number of lines
0.40	···	···	···	6.41	0	1
0.45	15.87	9.42	2	-3.99	0	1
0.50	17.13	19.78	4	-9.84	0	1
0.55	-5.55	6.76	6	0.64	0	1
0.60	1.28	11.76	7	2.08	0	1
0.65	9.08	15.83	8	-16.39	37.50	2
0.70	20.85	16.79	12	6.54	8.30	3
0.75	17.81	23.98	16	1.13	24.45	8
0.80	37.22	37.29	18	3.54	18.51	10
0.85	74.98	38.16	19	22.01	30.14	13
0.90	157.81	41.93	17	34.71	60.45	14
0.92	200.78	65.57	23	63.91	75.57	13
0.95	294.44	77.72	20	100.35	90.27	10